

UNITED STATES PATENT APPLICATION

For

MULTI-NOZZLE ASSEMBLY FOR EXTRUSION OF WALL

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MULTI-NOZZLE ASSEMBLY FOR EXTRUSION OF WALL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is based upon and claims priority to U.S. Provisional Application Serial No. 60/441,572, entitled "Automated Construction," filed on January 21, 2003, by inventor Behrokh Khoshnevis, This application is also based upon U.S. Provisional Application Serial No. _____, entitled "Automated Construction Using Extrusion," filed concurrently with this application, attorney docket number 28080-124, also by inventor Behrokh Khoshnevis. The entire content of both of these provisional applications is incorporated herein by reference.

GOVERNMENT'S INTEREST IN APPLICATION

[0002] This invention was made with government support under NSF Grant No. 9634962 and NSF Grant No. 9522982 awarded by the United States Government. The government has certain rights in the invention.

BACKGROUND

[0003] *Field*

[0004] This application relates to the construction of structures, including the construction of walls and roofs. This application also relates to the extrusion of material.

[0005] *Related Art*

[0006] Constructing homes, offices, boats and other structures has an ancient heritage. Despite all of the centuries of development, however, there can be difficulties and problems.

[0007] Construction is usually very labor intensive. Even a modest size structure usually requires the efforts of numerous individuals. This can be very costly. Simultaneously using the time of numerous individuals in an efficient manner can also be challenging.

[0008] The results of the construction effort can also be inconsistent. The appearance and quality of one structure can vary from another built from the same design. This can be caused by differences in the skills, efforts, supervision and techniques employed by those that work on the structures.

[0009] Construction may also result in wasted material. For example, when wood is used, standard, off-the-shelf lengths must often be cut to meet design requirements, resulting in waste.

[0010] Construction using manual labor can also be very time-consuming, requiring months and, in some instances, years to complete.

[0011] Construction can also be hazardous. Many construction workers are killed or seriously injured at construction sites, include about 500,000 in the United States alone.

SUMMARY

[0012] A multi-nozzle assembly may include a first nozzle configured to extrude material through a first outlet; a second nozzle configured to extrude material through a second outlet; and a third nozzle configured to extrude material through a third outlet, the third outlet being between the first and second outlets.

[0013] Each outlet may have a substantially rectangular cross-section.

[0014] The multi-nozzle assembly may include a nozzle position controller that is configured to controllably vary the height of at least one of the outlets with respect to the height of at least one of the other outlets.

[0015] The multi-nozzle assembly may include a first and/or second trowel configured to shape material extruded from the first and/or second nozzles, respectively.

[0016] The width of the first and the second outlet may be less than the width of the third outlet.

[0017] The multi-nozzle assembly may include an orientation-control mechanism configured to control the orientation of the multi-nozzle assembly. The orientation-control mechanism may be configured to control the orientation of the multi-nozzle assembly in three dimensions. The nozzle may be mounted on a XYZ motion control platform, such as a gantry robot. This may give the outlet 6 degrees of freedom.

[0018] The multi-nozzle assembly may include a material feed system configured to feed material to each nozzle. The material feed system may be configured to keep the material that is fed to the first and second nozzles separate from the material that is fed to the third nozzle. The material feed system may include a valve system configured to selectably cut off the flow of material to each of the nozzles in a controllable manner.

[0019] The multi-nozzle assembly may include a controllable gate configured to controllably block material extruded from at least one of the nozzles from flowing in a direction.

[0020] A construction method may include simultaneously extruding a first layer of two, spaced apart rims. After extruding the first layer of rims, a further layer of two, spaced apart rims may simultaneously be extruded, each directly or indirectly on top of one of the spaced apart rims in the first layer, along with a first layer of filler between the first layer of two, spaced apart rims.

[0021] The height of the first layer of rims and the first layer of filler may all be substantially the same.

[0022] The material used for the rims may be different than the material used for the filler. The material used for the rims may be plastic and the material used for the filler may be concrete.

[0023] The first layer of rims may be permitted to cure before extruding the further layer of rims and the first layer of filler.

[0024] The construction method may include, after extruding the further layer of rims, extruding a further layer of filler on top of the last extruded layer of filler without also simultaneously extruding a further layer of rims.

[0025] A wall may include a set of spaced apart rims, each comprised of a stacked set of separately-extruded layers; and a filler between the rims comprised of a stacked set of separately-extruded layers.

[0026] The rims may be made of a material that is different than the filler. The rims may be made of plastic and the filler may be made of concrete.

[0027] The wall may include one or more rectangular openings.

[0028] One of the layers of each rim may be extruded at the same time as one of the layers of the filler. The layers of each rim that may be extruded at the same time may be at a level within the wall that is different than the level of the layer of the filler that may have been extruded at the same time.

[0029] These as well as still further objects, features and benefits will now become clear from an examination of the detailed description of illustrative embodiments and the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

[0030] FIG. 1 illustrates one embodiment of a nozzle assembly that includes a single nozzle.

[0031] FIG. 2 illustrates the embodiment of the nozzle assembly shown in FIG. 1 being used to extrude a wall.

[0032] FIG. 3 illustrates another embodiment of a nozzle assembly that includes three nozzles.

[0033] FIGS. 4(a)-(c) illustrate the embodiment of the nozzle assembly shown in FIG. 3 being used to extrude a wall.

[0034] FIG. 5 illustrates the embodiment of the nozzle assembly shown in FIG. 3 being used to extrude a wall in an angled orientation.

[0035] FIG. 6 illustrates a nozzle assembly having an orientation control mechanism being used to construct an embodiment of a supportless roof.

[0036] FIG. 7 illustrates the supportless roof shown in FIG. 6 in its completed state atop a wall structure.

[0037] FIG. 8 illustrates another embodiment of a nozzle assembly that includes a slot in a central nozzle that accommodates reinforcement members.

[0038] FIG. 9 illustrates the nozzle assembly shown in FIG. 8 being used to construct a wall having reinforcement members.

[0039] FIG. 10 illustrates another embodiment of a nozzle assembly.

[0040] FIG. 11 illustrates certain components of the nozzle assembly shown in FIG. 10 in an unassembled form having a central nozzle at a height lower than interior and exterior nozzles.

[0041] FIG. 12 illustrates a bottom view of a portion of the nozzle assembly shown in FIG. 10.

[0042] FIG. 13 illustrates an embodiment of a nozzle including a controllable front and rear gate.

[0043] FIG. 14 illustrates one embodiment of a nozzle assembly using the type of nozzle shown in FIG. 13 being used to extrude a wall.

[0044] FIG. 15 illustrates the nozzle shown in FIG. 13 being used to extrude an insulation layer.

[0045] FIG. 16 illustrates a nozzle assembly using the nozzle shown in FIG. 13 being used to extrude a wall with a layer of insulation.

[0046] FIG. 17 illustrates another embodiment of a nozzle assembly having slots in a gate being used to extrude a wall with interlocked layers.

[0047] FIGS. 18 (a) and (b) illustrate another embodiment of a nozzle assembly having variable width nozzles.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0048] FIG. 1 illustrates an embodiment of a nozzle assembly that includes a single nozzle. As shown in FIG. 1, a nozzle assembly **101** may include a nozzle **103** having an outlet **105** (not visible in FIG. 1), a trowel **107**, and a trowel positioning controller, including a servo motor **109** and trowel linkage **111** and **113**.

[0049] Although shown as cylindrical, the shape of the nozzle **103** may vary. It may include an inlet **115** for material in a fluid or semi-fluid form.

[0050] The cross-section of the outlet **105** may vary. It may be circular, rectangular or of some other shape.

[0051] FIG. 2 illustrates the embodiment of the nozzle assembly shown in FIG. 1 being used to extrude a wall. As shown in FIG. 2, the nozzle assembly **101** is extruding a layer of material **203** while being moved in a horizontal direction **205**. The trowel **107** smoothens the exterior surface of the layer of material **203** as it is being extruded from the nozzle **103**. The lower surface **205** of the member that supports the nozzle **103** has an opening (not shown) through which the extruded material flows. The lower surface **205** may also act as a trowel to smoothen the upper surface of the layer of material **203** that is being extruded. An additional trowel (not shown) may also be included to smoothen the interior surface of the layer **203** that is being extruded. Alternatively, a sharp blade parallel to the first trowel may cut out excess material on the interior side to create a planar surface.

[0052] Referring again to FIG. 1, the height of the trowel **107** may be controlled by the trowel position controller which, as explained above, includes the servo motor **109** and the trowel linkages **111** and **113**. The height of the trowel **107** may be adjusted to

correspond to the height of the extruded layer **203**. By making the height of the trowel **107** adjustable, layers of different thickness may be extruded.

[0053] Although the smoothing surface of the trowel **107** and the underneath surface **205** are illustrated as being flat, other contours may be used instead.

[0054] Any type of material may be used and delivered into the inlet **115**, including cement or plastic. The material may be delivered in a liquid or quasi-liquid form and may include or receive additives or may have characteristics that cause the material to harden into a solid after extrusion.

[0055] As is apparent from an examination of FIG. 2, the nozzle assembly **101** may be moved horizontally in a back-and-forth motion, each time being elevated in height by approximately the thickness of each extruded layer. The collective effect is to create a wall **207** consisting of a stacked set of separately-extruded layers.

[0056] The horizontal direction **205** of the nozzle assembly **101** at the end **209** of a pass may be altered by 90 degrees into the direction **111**. This can produce an extruded wall that has a sharp right angle bend. Obviously, other types of changes in direction may be used to create other wall shapes, including curved walls and walls that join one another at angles other than 90 degrees.

[0057] FIG. 3 illustrates another embodiment of a nozzle assembly that includes three nozzles. As shown in FIG. 3, a nozzle assembly **301** includes an exterior nozzle **303**, an interior nozzle **305** and a central nozzle **307**. The exterior nozzle **303** may include an outlet **309**, the interior nozzle **305** may include an outlet **311**, and the central nozzle **307** may include an outlet **313**. Although each outlet is illustrated as having a rectangular cross-section, other cross-sectional shapes could be used instead, such as round or oval. The width of the central outlet **313** may be equal to, greater or less than the width of the exterior outlet **309** or the interior outlet **311**. The width of the exterior outlet **309** may be equal to or different than the width of the interior outlet **311**

[0058] A trowel **315** may be used to smooth the material that is extruded from the exterior outlet **309**, while a trowel **317** may be used to smooth the material that is extruded from the interior outlet **311**. The height of the exterior trowel **315** and the interior trowel **311** may, in turn, be controlled by trowel position controllers **319** and **318**, respectively.

[0059] FIGS. 4(a)-(c) illustrate the embodiment of the nozzle assembly shown in FIG. 3 being used to extrude a wall.

[0060] As shown in FIG. 4(a), a first layer of a wall **403** may be extruded by moving the nozzle assembly **301** in a horizontal direction and by extruding material only through the exterior nozzle **303** and the interior nozzle **305**. During this pass, no material may be extruded from the central nozzle **307**.

[0061] This approach may cause an exterior rim layer **405** and an interior rim layer **407** of material to be extruded. Since no material is being extruded during this pass from the central nozzle **307**, no significant force will be placed on the interior walls of the rim layers **405** and **407**.

[0062] The rim layers may then be left to cure and thus harden. Various approaches such as thermal and chemical may be used to speed up the curing process. For example, a torch, hot air blower, or microwave energy may be attached to the nozzle assembly **301** (not shown) to treat the extruded material and speed its curing. A judicious choice of material may also be made for the rims, that cures quickly, such as plastic.

[0063] As shown in FIG. 4(b) another rim layer may be extruded on top of the rim layer that has hardened. This may consist of a second exterior rim **413** being extruded on top of the first exterior rim **405** and a second interior rim **415** being extruded on top of the first interior rim **407**. A first filler layer **411** may also be extruded between the first rim layers **405** and **407** by extruding material from the central nozzle **307** at the same time that the second rim layers **413** and **415** are being extruded. The filler may

be of a much stronger material, such as cement. The filler material may or may not dry as quickly as rim material.

[0064] If the rim layers are able to cure quickly enough, and if their length is long enough, the nozzle assembly **301** may be able to return to the beginning of a pass to extrude the next layer of rims on top of the previous layer as soon as extrusion of the previous layer is complete. If the curing is fast enough, the nozzle assembly may instead be directed to extrude its next layers of material during the return traverse. Other sequences could also be followed, including a rest between traverses.

[0065] The process may be repeated until the height of the wall **403** reaches the needed level. FIG. 4(c) illustrates the wall **403** with six layers. After the last needed rim layers are extruded, the next pass may extrude only a filler layer, thus completing the wall structure.

[0066] Delaying the extrusion of filler layers helps insure that the rim layers will be strong enough to contain their neighboring filler layers. Of course, the extrusion of each filler layer need not always or even ever be exactly one traverse behind the extrusion of each neighboring rim layer. In other embodiments, the filler layers might be two or more layers behind the neighboring rim layers. Indeed, none of the filler layers might be extruded until after all or at least several of the rim layers have been extruded and hardened. In this embodiment, the entire wall filler or at least a large portion of it could be extruded in a single pass.

[0067] FIG. 5 illustrates the embodiment of the nozzle assembly shown in FIG. 3 being used to extrude a wall at an angled orientation.

[0068] Material to be extruded may be delivered through outer tubes **517**, **519**, **521** and **523**. Each of these outer tubes may contain within them a set of inner tubes, one channeling material to the exterior outlet **309** (see FIG. 3) and the interior outlet **311** (see FIG. 3), while the other channeling material to the central outlet **313** (see FIG. 3). In this way, the type of material that is delivered to the exterior outlet **309** and the

interior outlet **311** may be different from the material that is delivered to the central outlet **313**.

[0069] In another embodiment, each outer tube **517**, **519**, **521** and **523** may include three interior tubes, allowing a different type of material to be delivered to the exterior outlet **309** and the interior outlet **311** as well.

[0070] As also shown in FIG. 5 (and partially in FIG. 3), the nozzle assembly **101** may include an orientation control mechanism that can cause the outlets **309**, **311** and **313** to be pointed in almost any direction. Any type of control mechanism may be used, including a control mechanism that is capable of orienting the outlets in one, two or three degrees of freedom. With respect to the nozzle assembly **101** shown in the figures, an orientation control mechanism has been selected that allows the outlets to be oriented in three dimensions. The orientation control mechanism may include servo motors **501**, **503** and **505**, each controlling a separate axis of orientation. Of course, appropriate internal structures may be included to translate the motion of these servo motors into the necessary movement. In certain embodiments, positioning information may be sent back to a servo controller (not shown) and used in one or more feedback loops to maximize the accuracy of the positioning that is obtained. Appropriate material channeling chambers and gaskets may also be included (not shown) to ensure that the material continues to flow without significant leakage in the moving joints, regardless of the angular orientation that is directed. The nozzle assembly may itself be moved around by a XYZ positioning system, thus providing 6 degrees of freedom to the nozzle head.

[0071] Although nozzle assemblies having only a single or three nozzles have thus far been illustrated, it is to be understood that a different number of nozzles could be used, depending upon the application, such as two, four or even more.

[0072] FIG. 6 illustrates a nozzle assembly having an orientation control mechanism being used to construct an embodiment of a supportless roof. FIG. 7 illustrates the supportless roof shown in FIG. 6 in its completed state atop a wall structure.

Collectively, these figures demonstrate how the positional flexibility of the nozzle assembly can facilitate the construction of supportless roofs, such as vaults. Although a nozzle assembly having only a single nozzle is illustrated, it is to be understood that a different number of nozzles could be used, such as the triple nozzle assembly shown in FIGS. 3-5.

[0073] FIG. 8 illustrates another embodiment of a nozzle assembly that includes a slot in a central nozzle that accommodates reinforcement members. FIG. 9 illustrates the nozzle assembly shown in FIG. 8 being used to construct a wall having reinforcement members.

[0074] As shown in FIG. 8, a nozzle assembly **801** includes an exterior nozzle **803** having an outlet **805**, an interior nozzle **807** having an outlet **809** and a central nozzle set consisting of two nozzles **811** and **813** having outlets **815** and **817**, respectively, that are separated by an opening **819**. FIG. 9 illustrates how the opening **819** ensures that the nozzle assembly **801** does not collide with reinforcing members **821**, **823** or **825** during operation.

[0075] FIG. 10 illustrates another embodiment of a nozzle assembly. As shown in FIG. 10, a nozzle assembly **1001** may include an exterior nozzle **1003** and an associated trowel **1005**, an interior nozzle **1007** and an associated trowel **1009**, and a central nozzle **1011**. An inlet **1013** may be provided to receive material that is channeled to the central nozzle **1011** for extrusion, while an inlet **1015** may be provided to receive material that is channeled to the exterior nozzle **1003** and to the interior nozzle **1007** for extrusion. A bevel gear **1017** may be provided to rotate the nozzles.

[0076] Servo motors **1019** and **1021** may be used to control the height of the trowels **1009** and **1005**, respectively. A servo motor **1025** may be used to control an internal gate valve (not shown) that is used to regulate the flow of material to the exterior nozzle **1003**. Similarly, a servo motor **1023** may be used to control an internal gate valve (not shown) that is used to regulate the flow of material to the interior nozzle

1007. The flow of material to the central nozzle **1011** may also be regulated in a similar or different manner.

[0077] When making a curved wall, the rim material delivery rate may be different for the exterior and interior outlets. This may be effectuated by appropriate settings of the servo motors **1023** and **1025**. The valve may be near or away from the nozzle. The gate valves may be configured to controllably adjust the volume of flow, as well as to completely cut the flow off.

[0078] A servo motor **1027** may be used to control the height of the central nozzle **1011** with respect to the external nozzle **1003** and the internal nozzle **1007**. The heights of the external and/or internal nozzles may also be controlled in a similar or different manner.

[0079] FIG. 11 illustrates certain components of the nozzle assembly shown in FIG. 10 in an unassembled form with the central nozzle **1011** at a height lower than the interior nozzle **1007** and the exterior nozzle **1003**. Such a height differential may be useful in embodiments in which each central filler layer is extruded one pass behind each surrounding rim layer. The ability to control the relative heights of the nozzles may also be useful in applications in which there is a need to avoid occasional obstructions.

[0080] FIG. 12 illustrates a bottom view of a portion of the nozzle assembly **1001** shown in FIG. 10. It provides more detail on how the servo motor **1029** may control the height of the central nozzle **1011** with respect to the exterior nozzle **1003** and the interior nozzle **1007**. This detail includes a drive belt **1031** that causes ball screws **1132** and **1134** (see FIG. 11) to rotate and to thus cause a corresponding change in the elevation of the central nozzle **1011** due to interaction with associated threaded sleeves **1137** and **1139** (FIG. 11), respectively.

[0081] FIG. 13 illustrates an embodiment of a nozzle including a controllable front and rear gate. As shown in FIG. 13, a nozzle **1301** includes a controllable front gate **1303** and a controllable rear gate **1305**. The controllable gate **1303** may be controlled by a

gate controller, such as a servo motor **1307** and an associated coupling **1309**. Similarly, the controllable gate **1305** may be controlled by a gate control mechanism, such as a servo motor **1311** and an associated control mechanism **1315**.

[0082] FIG. 14 illustrates one embodiment of a nozzle assembly with the nozzle shown in FIG. 13 being used to extrude a wall. This embodiment allows the beginning and end of each extruded layer to be shaped with a sharp vertical surface by appropriate control of the gates.

[0083] FIG. 15 illustrates the nozzle shown in FIG. 13 being used to extrude an insulation layer. In this embodiment, a polystyrene filament may be fed through an electrically heated barrel **1501** so that molten plastic comes out through a nozzle **1503**. Compressed air may be mixed in as well to cause a bead of Styrofoam **1505** to be created. One or more of these layers may serve as insulation. Other types of polymers or other materials may be used instead.

[0084] FIG. 16 illustrates a nozzle assembly using the nozzle shown in FIG. 13 to extrude a wall with insulation. As shown in FIG. 16, a wall **1601** is being extruded by a nozzle assembly **1603** (shown only in part) that includes a stacked set of Styrofoam layers **1605**, **1607** and **1609**.

[0085] FIG. 17 illustrates another embodiment of a nozzle assembly having slots in a gate being used to extrude a wall with interlocked layers. As shown in FIG. 17, a gate **1701** includes slots **1703** and **1705** that cause corresponding ribs **1707** and **1709** to be created during the extrusion of the layer **1711**. These create interlocking ribs, such as the interlocking ribs **1713**, **1715** and **1717**, thus strengthening the wall that is extruded.

[0086] FIGS. 18 (a) and (b) illustrate another embodiment of a nozzle assembly having variable width nozzles. As shown in FIGS. 18(a) and (b), a nozzle assembly **1801** includes an exterior nozzle **1803**, a central nozzle **1805** and an interior nozzle **1807**. The width of the layer that is extruded from the exterior and interior nozzles **1803** and **1807**, respectively, may be varied by adjusting the relative separation of these nozzles, either manually or automatically under servo control. FIG. 8(a)

illustrates the exterior and interior nozzles being widely separated for a wider rim layer, while FIG. 8(b) illustrates these same nozzles being compressed together for a narrower rim layer. The flow rate of the extruded material may be reduced during a wider setting to insure that a full layer is extruded. The separating distance between the two rim nozzles may be varied during the extrusion of a structure to facilitate the construction of structures such as domes with a progressively thinning wall or to make certain walls, such as interior walls, thinner than other walls, such as exterior walls. Appropriate adjustments could also be made to make one rim layer thinner than the other.

[0087] A broad variety of construction applications may advantageously utilize one or more of the nozzle assemblies that have now been described.

[0088] For example, a nozzle assembly may include a roller that follows the extrusion and creates textures on the walls of the layers that are extruded.

[0089] A nozzle assembly may also be attached to an arm of a robotic system. Under computer or other control, the nozzle assembly may extrude the walls of an entire building, including several rooms. A gantry system may be used to support and position the nozzle assembly as it traverses the need paths. A positioning system may also be used to accurately position the nozzle assembly, such as a system that includes fixed reference points and a laser-guided detector mounted on the nozzle assembly.

[0090] Instead of one large gantry system and a single nozzle assembly traversing the layers of the entire structure, a plurality of nozzle assemblies may simultaneously be employed. Each may be attached and controlled by the arm of a small mobile robot dedicated to that nozzle assembly. The position and actions of this workforce of robots may be directed wirelessly by a central command station. Each one of these small robots, in turn, may include on-board tanks to contain the necessary materials that are extruded. These small robots may also return to a central filling station to refill their tanks when needed.

[0091] Rigid horizontal members may be used to facilitate the construction of windows, door openings and ceilings by bridging openings beneath them. To create a window, for example, the controller of a nozzle assembly may turn off the flow of material to all outlets in the nozzle assembly when the nozzle assembly is traversing an area that has been designated as the window opening. After the top of the walls surrounding the window have been extruded, a rigid horizontal member may be placed across the top of these walls to create the header of the window. One or more continuous layers of material may then be extruded on top of the header and the surrounding walls. A similar bridging approach may be used to create door openings. A ceiling may similarly be created by placing a series of neighboring structural members across the top walls of a structure, over which material may be extruded to give strength to the structure.

[0092] One or more of the robotic systems described above may also be used to place these structural members where needed, i.e., across the tops of window and door openings and across the tops of wall structures to provide a roof.

[0093] A variety of techniques may also be employed in an automated fashion to reinforce the strength of walls that are extruded. These techniques may include the automated insertion or embedding of clips across or within the rims of the walls periodically along their length. These reinforcement mechanisms may also include the insertion of rigid vertical members within the interior of the wall, including, in certain embodiments, rigid horizontal links between these vertical members. Again, all of this may be accomplished under automated robotic control.

[0094] Plumbing may also be installed as part of the automated process. Segments of plumbing pipe may be secured to other segments using automated installation and welding techniques.

[0095] Electrical wiring may similarly be installed as part of the automated process. Electrical wires may be housed in modules that are connected together within the walls, again under robotic control.

[0096] Sensors may be inserted within the structure to provide feedback regarding construction performance. After the structure is completed, these sensors may continue to be used to report on information about the structure, such as heat, humidity, and deformation.

[0097] Tiling and even painting may similarly be done under robotic control.

[0098] A mixer may also be provided in association with a nozzle assembly to allow the components of a fast-curing material to be mixed near the head of the assembly.

[0099] By combining some or all of these features into a single system, the vast majority of a sound and quality structure may be built according to custom specifications very quickly, efficiently, accurately and with few personnel.

[00100] Although now having described certain embodiments of nozzle assemblies, construction methods and walls, it is to be understood that the concepts implicit in these embodiments may be used in other embodiments as well. In short, the protection of this application is limited solely to the claims that now follow.